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ROUGHNESS CHARACTERISTICS OF PLANE SURFACES BASED ON VELOCITY S--ETC(U)
JAN 81 M J KINGS, K B CHUAH, S T OLSZOWSKI N00014-78-G-0059

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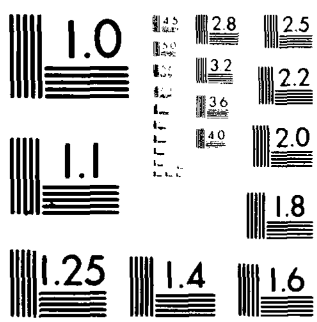
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ROUGHNESS CHARACTERISTICS OF PLANE SURFACES BASED ON VELOCITY SIMILARITY LAWS.		5. TYPE OF REPORT & PERIOD COVERED Conference Proceedings
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) M.J. KING, K.B. CHUAH, S.T. OLSZOWSKI, T.R. THOMAS		8. CONTRACT OR GRANT NUMBER(s) N00014-78-G-0059
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mechanical Engineering, Teesside Polytechnic, Middlesbrough, Cleveland TS1 3BA, U.K.		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 067-629
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Navy: Office of Naval Research Washington D.C.		12. REPORT DATE January 1981
		13. NUMBER OF PAGES 9
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

LEVEL II

16. DISTRIBUTION STATEMENT (of this Report)

Distribution unlimited.

DTIC SELECTE FEB 17 1981 D
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Paper to be presented at 1981 ASME/FED Spring Conference Boulder, Colorado: Turbulent Boundary Layers on Rough Surfaces.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Some common problems of surface measurement and ambiguities of description are discussed and it is shown that numerical discrepancies of a factor of 20 can result from the latter. A comprehensive programme of roughness measurement on working surfaces is described associated with a programme of flow measurement in an open flume in an attempt to isolate a range of surface wavelengths responsible for drag. A feasibility study of roughness measurement on coated surfaces is followed by measurements on hull replicas, gravel and coated steel

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plates. Measurements of an ablative coating system before and after an ocean voyage demonstrates a loss of roughness associated with a smoothing of peaks. Flow measurements suggest that surface wavelengths of less than 100μm do not interact with the fluid.

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INTRODUCTION

A great deal of work has been published on the interaction between surface roughness and fluid flow. Much of this work is seriously flawed by an imperfect understanding of the nature of roughness. This is especially true of flow over flat rough plates, with its important applications to ship hydrodynamics.

The velocity similarity laws have proved to be successful in correlating turbulent shear flows, both internal and external, and for smooth and rough surfaces. This has led to roughness characterisation which has been shown to be the same for developed pipe flow and developing two- and three-dimensional boundary layer flows.

A flat plate analogy is commonly used for the purpose of calculating wall friction on ship-hulls. It has long been recognised that surface roughness has a major effect on the wall friction. However, the simple one-dimensional measure of roughness height, such as the mean apparent amplitude or standard deviation, has proved inadequate to quantify uniquely the effect of surface roughness on the hydrodynamic characteristics of turbulent shear flow.

In this paper we review briefly some problems of surface characterisation and of flow measurement; we propose a new methodology based on a unification of conventional hydrodynamics and engineering metrology; we describe some of the first results of this approach, including systematic roughness measurements of flow measuring systems and of ablating coating systems.

PROBLEMS OF SURFACE CHARACTERISATION

A variety of descriptors occur in the literature of hydrodynamics to characterize roughness height variations, e.g. sand-grain roughness, mean apparent amplitude (MAA) and average roughness (R_a). These are often treated as if they were sufficient, equivalent, and intrinsic properties of the surface topography. They are none of these things. We will look at the three qualifiers in order.

Sufficient. The three parameters quoted above all describe variations of height only. Thus two surfaces with the same value of MAA might have quite different "textures". For instance, a profile with the shape of a repeated letter U would present a series of cusps to a fluid flowing over it, while if it were inverted it would present a series of smooth undulations. Although the hydrodynamic properties of the former and the latter might well be quite different, MAA and the other parameters would be unable to discriminate between them.

Thus at least one additional parameter is necessary to describe the texture. Many have been proposed and used, such as mean slope, (m), peak radius of curvature, number of high spots per unit length and so on; references to a comprehensive list may be found in Thomas & King (1). Luckily it can be shown that for a random surface, as most real surfaces are, most of these parameters are simply different ways of presenting the same information (2).

In fact if a surface has a Gaussian height distribution and is isotropic, that is its texture looks the same in all directions, its statistical geometry can be specified completely in terms of the first three even moments of a profile power spectrum (3); the zeroth moment is related to the average roughness, the second to the slope, and the fourth to asperity radius of curvature. However, there are certain difficulties in defining the moments, which will be discussed below.

If the surface is not Gaussian, then higher moments of the height distribution will be required to describe it. Use of the third and fourth central moments, known respectively as skewness (Sk) and (4) kurtosis (K) is usual. Skewness, as its name suggests, is a measure of the asymmetry of the distribution, and it seems likely that, as proposed by Musker & Lewkowicz (5), it will have some hydrodynamic influence.

Equivalent. The mean apparent amplitude is found by measuring the distance between the highest peak and lowest valley in each of a number of consecutive sample lengths into which the profile is broken up and averaging these distances over the total number of sample lengths (6). Its definition thus has much in common with the average peak-to-valley height R_z defined in the German standard DIN 4762 (not to be confused with different parameters using the same symbol in the British and international roughness standards). It is well known that the numerical value of this parameter can vary between 3 and 10 times the measured value of R_a on the same surface (e.g. 7). This might be expected as the latter measures an average excursion from the mean while the former depends on extreme excursions.

Sand-grain roughness k is usually defined as the average particle size or diameter of the sand grains used to construct the surface. Grigson (8) has pointed out that the average roughness of such a surface must be much smaller and has suggested a value of $R_a = 0.29k$. Consider a model of spheres of equal radius r embedded at random in an adhesive matrix (9). We assume that no sphere is embedded to a depth less than its radius otherwise it would be swept free, and that the distribution of grain centre heights is rectangular, i.e. it is *equally likely that a grain* will take up any position within the adhesive. It can be shown that the distribution of heights z on the resulting surface

$$p(z) = \{r - (2rz - z^2)^{\frac{1}{2}}\}/r^2$$

From our intial assumptions the distribution can only exist between 0 and r, and its n th moment will therefore be

$$\mu_n = \int_0^r z^n \, p(z) \, dz$$

giving the first and second moments as

$$\mu_1 = r\,(5/6 - \pi/4)$$

and $$\mu_2 = r^2(1 - 5\pi/16)$$

The variance is *the square of the RMS roughness* σ *and* is related to the first and second moments by

$$\sigma^2 = \mu_2 - \mu_1^2$$

So finally

$$\sigma = 0.126\,r = 0.063\,k$$

The average roughness is numerically about 30% smaller than the RMS roughness: the difference is usually neglected in practice because of the very large scatter in roughness measurements discussed below. So workers who take the sand-grain roughness as a measure of the average roughness are probably overestimating the latter by a factor of about 20.

Intrinsic. None of the height or texture parameters yet discussed is an intrinsic property of a surface. That is, a surface cannot be said to possess a certain average roughness or a certain mean slope without further qualification. Height parameters are sensitive to long surface wavelengths and a sample length, usually implemented in practice by a high-pass filter cutoff wavelength, must be specified in order to define them. Texture parameters are sensitive to short wavelengths and must be defined by a low-pass cutoff, usually related to the sampling interval of the analogue-to-digital converter when measurements are by digital techniques. For many surfaces average roughness increases as the square root of the high-pass cutoff (10) while mean slope varies inversely as the square root of the low-pass cutoff (11).

The numerical values of most roughness parameters, then, depend on the bandwidth of surface wavelengths selected by the experimenter. Any given measuring instrument will of course have an inherent range and resolution, but there is no a priori reason why this should coincide with the portion of the spectrum of wavelengths which takes part in any given physical interaction of the surface being measured. A better way to proceed is by "functional filtering" of the raw surface data (11) using cutoffs deliberately related to the physical problem under investigation. This has another advantage: the power spectra of many surfaces are such that the moments referred to above depend on the cutoffs, hence defining these for a particular surface interaction defines the entire statistical geometry relevant to that interaction.

Finally there is the difficulty that on real surfaces the measured values of all roughness parameters are subject to large variations due to random sampling. This has been reported in the hydrodynamics literature (e.g. 12) for surveys on ship hulls, and has been explained as a consequence of the difficulties of maintaining an even finish on so large and disparate a surface. It is found even on carefully machined surfaces, however: the coefficient of variation for 10 parallel profiles measured 1mm apart on a ground surface can be 20% - 30% for R_a and 50% or more for extreme-value parameters analogous to MAA (13). It is a consequence essentially of the statistical problems discussed above and a relationship exists between the uncertainty in a particular measurement and the bandwidth of wavelengths measured (14). Thus any roughness measurements based on a single profile must be treated as subject to considerable uncertainty. The point has been restated recently by Karlsson (15), who found differences of 30% or more between his own roughness measurements and measurements on the same surface at Liverpool.

The most ambitious attempt to correlate roughness *measurements with hydrodynamic data reported to date* is that of Musker & Lewkowicz (5), and it is interesting to review their work in the light of the foregoing discussion. They propose a modified roughness parameter

$$h' = \sigma\,(1 + am)\,(1 + b\,Sk\,K)$$

where a and b are empirical constants, on the grounds that increasing slope, skewness and kurtosis are all likely to increase drag. They found that the roughness functions so obtained from their measurements collapsed on to a single curve for a = 0.5 and b = 0.2 at a high-pass cutoff of 2mm, whereas if MAA alone was used the resulting scatter could not be resolved.

Their physical assumptions seem plausible, though as kurtosis is sensitive to valleys, which are unlikely to cause drag, as well as to peaks, one may suspect that its hydrodynamic effect is already described by the skewness. It is not clear whether the values of slope in the above expression should be read in degrees or radians; even if the former, it is a little surprising that the low values of a

and b reported are able to change h' sufficiently to reduce the scatter appreciably on a logarithmic plot, particularly when one remembers that skewness can take a negative value and that both it and kurtosis are subject to large uncertainties due to random sampling. It would be interesting to know how sensitive the mean residual of their roughness function was to the numerical values of a and b.

If more than one roughness parameter is thought likely to influence a surface interaction, and if no firm theoretical basis exists for a prediction, a useful approach is to plot one roughness parameter against another for each surface and to examine whether the resulting distribution in two-dimensional space is correlated in any way with the physical performance of the surfaces. This approach was first applied by Hirst and Hollander (16) in an investigation of wear by plotting RMS roughness against correlation length for a number of surfaces, leading them to identify regions and hence joint values of these parameters characteristic of high and low wear.

Recently Byrne (17) has applied a similar approach to an analysis of ship hull roughness measurements by plotting a parameter similar to MAA against a statistical bandwidth parameter related to the moments of the power spectrum referred to above. Although no drag measurements were available for comparison, he was able to identify a region characteristic of new ships. This approach is potentially a very powerful one and may be extended by discriminant analysis to assess the relative importance of n parameters by observing their clustering in n-dimensional space (18).

EXPERIMENTAL PROGRAMME

A universal "roughness function" in terms of the statistical geometry of the surface is being sought for the prediction of, principally, the surface shear stress. Some modest progress towards this goal has been reported by Musker & Lewkowicz (5) for a restricted class of surfaces produced by double replication inside circular tubes. A more direct approach is being made at Teesside Polytechnic by carrying out flow studies on specimen ship plates, placed at the bottom of an open flume, and performing statistical analysis of a comprehensive survey of their surfaces.

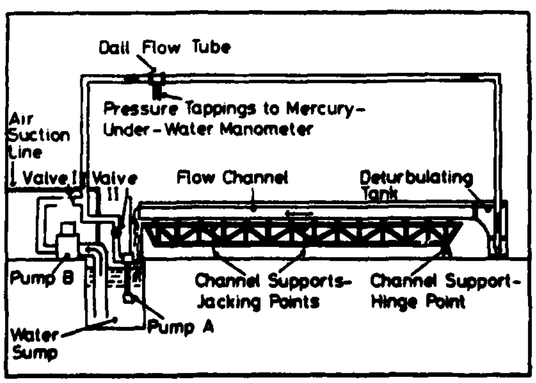


Figure 1. Schematic of open-channel flow measuring system.

Flow measurements

The open channel is of square section, 30cm wide and 20m long. Its inclination can be varied continuously from zero to 1 in 60. The rigid steel frame allows precision levelling of the bottom of the channel whose sides are made of toughened glass plates. Water is recirculated by a large capacity pump and the variable flowrate is measured by means of a differential pressure type flowmeter. An adjustable weir at the downstream end of the flume permits variation in the depth in conjunction with the slope. The specimen plates are located at the downstream section where the flow is made to approach the steady uniform condition (Figure 1).

Although a valid basis for the analysis of developed flow in wide rectangular channels is provided by semi-logarithmic velocity distribution, the limitations on the width-depth ratio introduces significant departures from the ideal two-dimensional flow model. The corner effects on the momentum balance are being studied using glass plates along the bottom of the channel. The beneficial effect of the restriction on the width-depth ratio is the enhancement of the stability limit which permits operation at higher supercritical flow velocities.

The developing tranquil flow in the upstream channel section was used to obtain a tripped turbulent boundary layer along test surfaces located at the floor of the channel. The surfaces consisted of: (a) relatively smooth primed steel plates, (b) a positive replica of a ship hull, and (c) a relatively rough gravel surface. Measurements were taken over a range of free stream velocities of 0.35 ms^{-1} to 0.85 ms^{-1}. Hot film anemometry using a boundary layer probe was used to measure the velocity profile across several sections along the plate/replica/gravel surface in the streamwise direction. These profiles were analysed to determine the local skin friction coefficients using three different methods.

Roughness measurements

Instruments. No one instrument could cover the range of surface wavelengths and vertical displacements occurring in this investigation. A number of instruments and measuring systems were employed and are identified by letter in Table 1. In order of increasing wavelength range, they were as follows:

Instruments A, B and C were stylus instruments for measuring the shorter wavelengths. Instrument A was a Talysurf 3 bench stylus instrument (Rank Taylor Hobson, Leicester) with a gauge length of 8mm and a vertical range of 0.1mm. The diamond stylus was in the form of a truncated pyramid with 90^o included angle and tip dimension $3\mu m$ in the direction of stylus travel. Instrument B was a Ferranti Surfcom 30B bench stylus instrument (Tokyo Seimitsu, Tokyo) with a gauge length of 100mm and a vertical range of 0.5mm. The diamond stylus was conical with a 90^o included angle and $2\mu m$ tip radius. Instrument C was a Talylin stylus instrument (Rank Taylor Hobson, Leicester) with a gauge length of 50mm and a vertical range of 0.5mm, which could be doubled if required by a lever extension at the expense of inverting the signal. A steel stylus with an included angle of 30^o and a tip width of 0.5mm was normally used, but the lever extension employed a spherical stylus of radius 1.6mm to make it compatible with BSRA wall gauge measurements (12).

The output signal from instruments A and C was sampled at equal horizontal intervals by a data log-

ging system with a discrimination of 10 bits and recorded on punched paper tape for subsequent computer analysis off-line. The sampling interval was 2μm for instrument A, 100μm for B and 190μm for C.

Systems D, E and F were employed to deal with longer wavelengths: Instrument D was a Mercury 3-axis coordinate measuring machine (Ferranti, Edinburgh) with a gauge length of 1m, a vertical range of 20cm and a vertical resolution of 10μm. A ball-ended probe of 0.5mm radius was used to record measurements at horizontal intervals of 1mm on punched paper tape. System E used a dial gauge with a 120cm straight edge as reference. The dial gauge had a ball-ended measuring probe with a radius of 1mm and readings were taken manually at horizontal intervals of 5mm. System F used a Talyvel electronic level (Rank Taylor Hobson, Leicester) which measured slopes to a baselength of 9cm. Slope readings were taken manually at horizontal intervals of 9cm, the baselength of the instrument. For both systems readings were recorded manually on punched paper tape for subsequent computer processing.

In addition to these instruments a BSRA wall gauge (12) and a Talysurf 105 portable stylus instrument were employed on isolated occasions. These could both be used for in situ measurements, as also could systems C, E and F. For the other systems where necessary coupons from the larger surfaces were brought to.
same computer software, written in Fortran, was used in processing all the measurements except those of system B (though the data from system F needed pre-processing to convert slopes to heights) and has been described in detail elsewhere (19) System B was driven by a substantially modified version of this program translated into Basic; this also has been described elsewhere (20).
Each measurement consisted of a single sample length except where identified otherwise in Table 1.

Measurements. Most ship hulls have been treated with a coating system, and it seemed important to establish as a preliminary whether painting can itself change surface roughness, and whether the hard sharp stylus of the measuring system will faithfully reproduce the roughness of the relatively soft coating (21).

Measurements were made on a shotblasted steel surface sprayed with primer and then brush-coated with successive layers of marine paint. To examine stylus damage, glass was painted and the surface was scratched with the stylus at intervals as it dried. Scratches made after the recommended drying time were imperceptible. The stylus was then dropped onto the surface to look for elastic deflection of the paint, but none could be found.

To ensure that the same section was examined before and after drying, the testpiece was mounted on a relocation table, (22) which made sure that the testpiece was replaced in exactly the same position under the stylus. The table was modified so that it would work for a week and the testpiece, measured daily, was relocated perfectly.

Profiles 8mm long were measured in the middle of the primer-coated testpiece with instrument A. The testpiece was removed for each overcoat, replaced, and measured again. This was done for five overcoats, allowing the paint to dry for 24 hours before each measurement (Figure 2). The experiment was repeated and this time the profiles were recorded digitally.

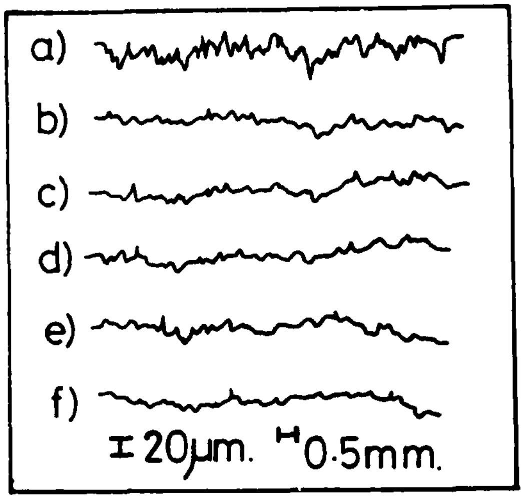


Figure 2. Relocated profiles of a shotblasted steel surface after coating with (a) primer (Test 6 of Table 1) (b-f) successive top coats (21).

As no changes were observed visually in the first experiment after the second overcoat, the repeat was carried out for two overcoats only. The results were analysed by computer.

The first overcoat made the surface about two-thirds as rough, but the second overcoat made it only 11% smoother. The roughness of the top 0.1% of the surface did not change, suggesting that paint may not cover the highest peaks. Slopes and peak radii decreased by 48% and 58% respectively, and there were fewer high slopes, probably due to the rheology of the paint. Wavelengths of between 20μm and 200μm were reduced in height, but the surface was just as rough below 20μm, a dimension corresponding to the size of the larger particles of filler. This suggests that a smooth surface could actually be made rougher by painting, an effect which we confirmed by experiment.

The first analytical roughness measurements were made on a positive acrylic replica supplied by the British Ship Research Association of the corroded hull of a tanker (Test 1 in Table 1) and on an acrylic replica supplied by Shell International of another tanker hull (Test 2). Subsequently roughness measurements were carried out on the three surfaces used for flow measurements (Tests 3-15). These were: a set of shot-blasted steel plates coated with primer (Tests 3-6); a gravel surface (Test 7); and a 5m positive replica of a tanker hull cast in our own laboratory, from a negative replica supplied by Shell Research (Tests 8-11). This last surface was brush coated with a marine coating with a total of three layers and roughness measurements were made after each coating. Measurements were also made in two directions at right angles after coating to see whether the use of a brush had imparted any directional properties to the surface (it had not). Finally some measurements (Test 16) are included for comparison from a separate programme of roughness measurements on competition rowing boats; this particular example was from a positive replica of part of the glass fibre hull of a scull.

surface	Instrument	Test	λ_1 (mm)	$\lambda_2/2$ (μm)	σ (μm)	MAA (μm)	Sk	K	m (degrees)
BSRA replica of corroded hull (5 measurements)	C	1	50	190	117 (35)	519 (140)	0.53 (0.52)	2.97 (0.71)	20.5 (9.1)
Shell replica of oil tanker hull (5 measurements)	C	2	50	190	41.5 (7.3)	185 (23)	0.11 (0.47)	2.88 (0.44)	1.50 (0.21)
shotblasted steel plate with primer	F	3	1.7×10^4	9×10^4	311	2166	-0.32	3.9	0.063
	E	4	1140	5000	80	341	-0.95	3.1	0.079
	C	5	102	190	13	78	-0.16	2.9	1.2
	A	6	8	2	7.0	37	0.06	2.2	6.4
gravel	D	7	270	1000	959	5253	-0.07	3.0	17
5 m Shell replica of oil tanker hull	F	8	4830	9×10^4	1308	6264	0.13	3.2	0.46
	E	9	1140	5000	653	2813	0.10	2.4	1.2
	C	10	50	190	145	896	-0.92	5.3	6.5
	B	11	25	100	41	189	0.60	3.1	5.8
as Tests 8 - 11 with 1 surface coating	F	12	4830	9×10^4	1189	4845	-0.08	2.3	0.45
	E	13	1180	5000	725	2897	0.04	2.2	1.2
	C	14	50	190	155	931	-1.1	5.8	6.6
	B	15	25	100	43	198	0.08	2.2	4.3
replica of Cameron scull (4 measurements)	B	16	0.8	10	0.085 (0.013)	0.440 (0.075)	-0.02 (0.17)	2.50 (0.12)	0.44 (0.24)

Table 1. Roughness parameters of various surfaces measured at high-pass cutoff wavelength λ_1 and low-pass cutoff λ_2 (= 2x sampling interval). Figures in brackets are standard deviations.

In recent years so-called ablative coating systems have become commercially available. One of these systems, self-polishing copolymer (SPCP) paint (International Paints, Felling-on-Tyne), is claimed to ablate preferentially in turbulent flow, so that the tops of the higher asperities are polished off in service. We carried out roughness measurements with instrument C on four plates coated with SPCP in June 1975. They were bolted to the bilge keel of a supertanker and subjected to an ocean voyage of several months, and we examined them again in March 1976. Care was taken to ensure that the roughness profiles were measured along the same sections as nearly as possible before and after the voyage.

RESULTS AND DISCUSSION

The main body of roughness results are summarised in Table 1. Several of the points made above may be seen to be confirmed: the considerable disparity between MAA and RMS roughness; the scatter in measurements of individual parameters; the dependence of all roughness parameters on high- and low-pass cutoffs. On any scale, however, the measurement values of skewness and kurtosis are not inconsistent with a Gaussian distribution of heights (Sk = 0, K = 3). A profile of the steel plates measured on the largest scale (Test 3) shown in Figure 3 is remarkably similar in general appearance to the profile of the same surface on a much smaller scale reproduced in Figure 1a, a striking example of self-similarity (23). A composite power spectrum of this surface (Figure 4), while containing local anomalies, shows overall a trend toward the square-law form. This spectrum is believed to cover a wider band of surface wavelengths than any previously reported.

The coating used on the 5m Shell replica was a thixotropic anticorrosion marine paint (Silver Primocon, International Paints, Felling-on-Tyne). Results for the first coat only are presented in Table 1 (Tests 12-15) as subsequent coatings had no

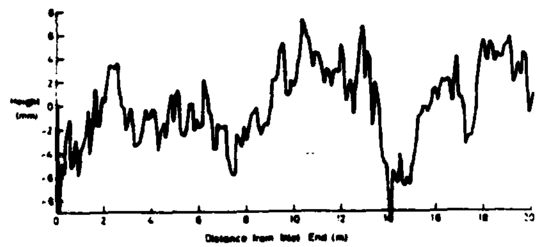


Figure 3. Profile of three steel plates butted end to end in the bed of the 20m flow channel measured in situ by instrument F (Test 3 of Table 1) (24).

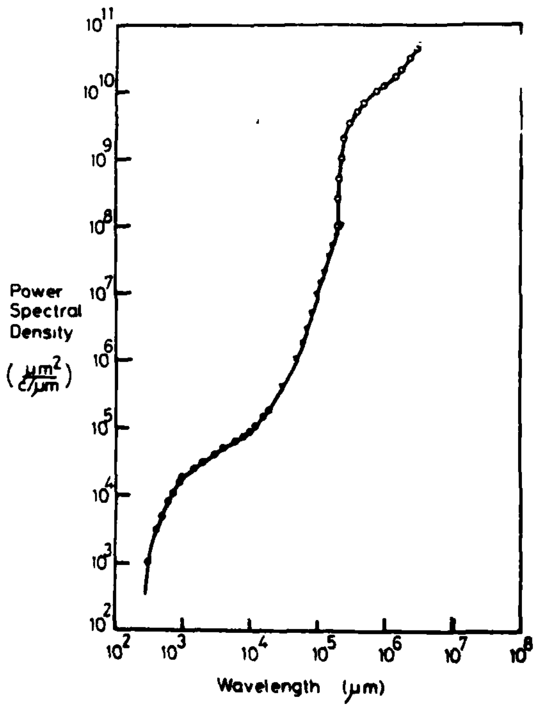


Figure 4. Composite power spectrum of shotblasted steel plates (24). Solid circles, instrument C; triangles, instrument E; open circles, instrument F.

perceptible effect on the microgeometry. No significant change is evident in any roughness parameter over any portion of the spectrum of wavelengths measured. This is not unexpected for the longer wavelengths, but some change would have been looked for at the shorter wavelengths, and indeed it appears from the relocated profiles that painting has removed some of the smallest undulations. From Table 1, then, painting has not affected any wavelengths longer than 100μm.

Measurements made with the BSRA wall gauge at its high-pass cutoff of 50mm yielded on the shot-blasted steel plate with primer over 10 sample lengths of 50mm each yielded a value of 55+ 19μm for the MAA. This is in reasonable agreement with the MAA of 78μm measured on the same surface with the Taylin at 102mm sample length (Test 5 of Table 1). The RMS roughness of 0.085 + 0.013μm measured on the scull replica at 0.8mm high-pass cutoff (Test 16) is comparable with a large number of other roughness measurements made by us directly on the hulls of competition rowing boats with a Talysurf 105. If scaled up by the square-root law this would be equivalent to 0.67μm at the BSRA standard 50mm cutoff: a smooth surface indeed.

The results of the ablative coating measurements are summarized in Table 2. Integers represent the number of consecutive 50mm sample lengths over which the data are averaged, and vary from parameter to parameter as the roughness of some sample lengths exceeded the range of the instrument. Three of the plates, MT3, MT1 and MB1, were originally much rougher than the fourth, MB2; the latter's RMS and MAA roughnesses were little affected by its ocean voyage, whereas the first three all became smoother. All four ended with RMS roughnesses of between 12 and 17μm (apart from the LHS of plate MB1 which seems to have started uncharacteristically rough). It is tempting to speculate whether this narrow range of roughnesses is related to the thickness of the laminar sublayer.

Peak radii of curvature have increased on all four plates and slopes have decreased (except on the RHS of Plate MB2). The inference seems clear, that the tops of the highest asperities have in fact been polished off. This is confirmed by comparing the power spectra before and after the voyage (Figure 5), where the ratio of power before and after is almost independent of wavelength; this is characteristic of a profile with a censored height distribution (25) where the surface is removed evenly down to a new level.

The experimental flow data were plotted non-dimensionally using the inner law for the boundary layer velocity distribution. The plots show the existence, in each case, of a relatively narrow logarithmic region consistent with the low values of the momentum thickness Reynolds number. The results of the flow and surface analysis for the primed steel plates are consistent with published results for hydrodynamically smooth surfaces. The gravel surface data are displaced downwards by a significant distance in accord with the accepted interpretation of the roughness effect; those for the replica of a ship hull are displaced downwards relative to the smooth turbulent line but only very slightly.

The surface and flow data were correlated along the lines suggested by Musker and Lewkowicz (5), using the modified roughness Reynolds number (Figure 6)

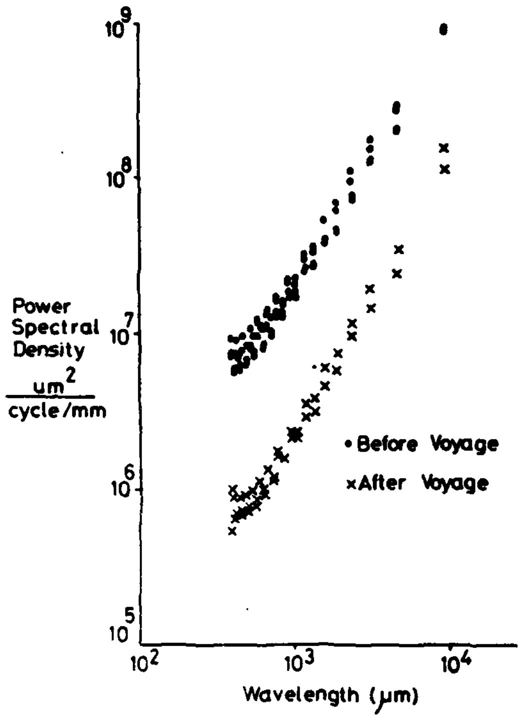
$$ku_\tau/\nu = (\sigma u_\tau/\nu)(1 + am)(1 + bSkK)$$

and the roughness function

$$\chi = 5.62 \log_{10} \chi^*$$

where

$$\chi^* = (7.752\ ku_\tau/\nu)/\{\exp(-0.005ku_\tau/\nu) + 0.44ku_\tau/\nu\}$$



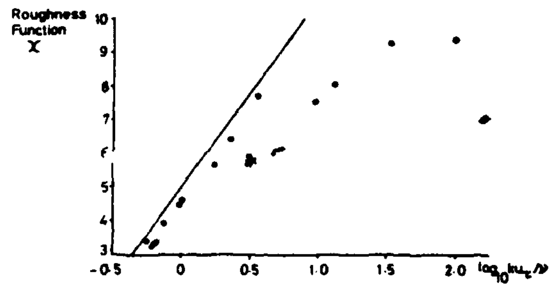


Figure 6. Variation of roughness function with roughness Reynolds number. Open circles, steel plates; +, 5m replica; x, 5m replica after coating; pierced circles, gravel; filled circles, tests R550, R253, R173 of Ref. 5. Straight line is for a hydraulically smooth surface.

Figure 5. Power spectrum of Plate MT1 coated with SPCP paint before and after an ocean voyage (see Table 2).

parameter		MB 2 RHS	MB 2 LHS	MT 3 RHS	MT 3 LHS	MT 1 RHS	MT 1 LHS	MB 1 RHS	MB 1 LHS
σ (μm)	before	16.0 (4.2) 9	14.0 (2.4) 10	51.0 (7.0) 10	61.0 (6.3) 10	52.0 (2.8) 9	68.0 (9.0) 9	87.0 (5.1) 10	159 (19) 11
	after	16.8 (2.5) 12	12.7 (1.2) 11	16.1 (1.4) 9	17.4 (2.6) 9	12.3 (1.1) 10	17.3 (2.5) 10	16.2 (0.76) 9	34.8 (5.1) 9
MAA (μm)	before	47.0 (6.8) 8	45.0 (6.0) 8	323 (49) 10	379 (47) 10	390 (1.5) 9	439 (77) 10	502 (83) 11	806 (81) 11
	after	60.0 (7.1) 12	48.5 (4.1) 11	108 (12) 9	117 (18) 9	83.2 (8.8) 10	106 (16) 10	89.9 (3.4) 9	181 (24) 9
MPRC (mm)	before	27.0 (0.28) 8	20.0 (4.9) 10	2.13 (0.068) 10	1.82 (0.061) 10	1.47 (6.36) 9	2.00 (0.061) 10	1.49 (0.34) 11	1.25 (0.17) 11
	after	67.0 (3.3) 11	60.6 (3.1) 11	6.4 (2.6) 9	5.1 (2.0) 9	11.4 (0.43) 10	10.6 (1.4) 10	2.90 (0.31) 9	5.62 (0.42) 9
m (degrees)	before	0.549 (0.073) 7	0.83 (0.24) 10	5.81 (0.59) 10	7.05 (0.46) 10	6.08 (0.97) 8	7.3 (0.73) 10	9.28 (0.81) 10	17.3 (2.1) 11
	after	0.79 (0.17) 10	0.558 (0.054) 11	1.77 (0.22) 9	2.10 (0.70) 9	1.24 (0.11) 10	2.20 (0.28) 10	2.66 (0.11) 9	3.98 (0.64) 9

Table 2. Roughness parameters measured parallel to the streamwise edges of each of 4 plates coated with SPCP paint before and after an ocean voyage. Figures in brackets are standard deviations, integers are numbers of sample lengths, MPRC = mean peak radius of curvature.

Except for the results appertaining to the coarse gravel surface, the results conform reasonably well with those obtained by the Liverpool researchers for their replicas of ship surfaces. However, in view of the lack of precision in evaluating the friction velocities in the channel experiments (mainly because of the simplifying assumptions made) and the very limited range of flow conditions in these tests, it would be injudicious to make a definite comment on the validity of their proposed method of surface roughness characterisation, or whether a simpler method is likely to arise from our continued investigations. Test surfaces which are about to be tested in the developed region of the channel flow include new plates coated with self-polishing paint applied with different microtopographies.

CURRENT WORK

Fundamental studies will first be undertaken using glass plates laid along the bottom of this glass-sided channel in order to explore the smooth turbulent flow regime and hence quantify the "corner effects" under those conditions. Subsequently, a series of tests will be carried out on several specimens of ship plates sprayed with anti-fouling self-polishing paint to different magnitudes and microtopography of surface roughness. Surface measurement of small samples of these plates will be made in parallel, using stylus instruments and characterised using statistical theory.

Flow measurement is carried out at the developed part of the uniform turbulent channel flow i.e. the flow is allowed to develop over 2/3 of the channel length. In order to increase the Reynolds number it is necessary to operate at depths below critical i.e. Fr >1, which necessitates the use of non-intrusive velocity and depth measurement techniques. A single channel Laser-Doppler Anemometer (LDA) is being used for these purposes. As the LDA has some areas of uncertainty particularly in its operation at regions very close to the solid boundary a hot-film anemometer with boundary layer probe will thus be used in addition to give a comparison.

The LDA is mounted in a sturdy traversing gear which provides adequate movement in three co-ordinate directions and easy adjustment between the transmitting and receiving optics to enable operation and focussing in forward scatter. A target probe is incorporated to enable the location of the beam crossing to be ascertained with reference to the bed plate and channel side-walls. Displacement transducers are used to resolve and indicate the position of the measuring volume i.e. the intersection of the laser beams in the flow stream along the coordinate axes. The output of the LDA signal processor is fed, together with the outputs of the displacement transducers, to a data logger which can be linked on-line to a microcomputer or off-line to main frame computer for flow analysis.

CONCLUSIONS

We have tried to show that problems of the measurement and characterization of surface roughness are central to the hydrodynamics of rough surfaces and that serious difficulties will ensue if different descriptions of roughness are confused with each other. In support of this argument we have presented a careful and extensive survey of the roughness parameters of a number of surfaces associated with flow problems. In the course of this we have been able to obtain some evidence that at least one ablative coating system becomes smoother in service.

All the surfaces measured in this series of tests exhibited statistical geometry very similar on every scale and characteristic of a wide range of natural and man-made surfaces. Such surfaces have a Gaussian height distribution and a square-law power spectrum, and these also were shown by our test surfaces. If this is generally true the task of the theoretician will be greatly simplified, as the geometrical properties of these surfaces are quite easy to derive and have been extensively treated in the literature of engineering metrology.

In the current state of the art we see the most important unresolved problem in the field as the definition of the range of surface wavelengths responsible for interacting with fluid flow. In the absence of a convincing theoretical approach our proposed method of attack is to combine flow and roughness measurements in order to see whether modifications to the surface microgeometry on a particular scale can be correlated with changes in hydrodynamic properties. The limited tests which we have so far been able to make indicate that under our experimental conditions changes in wavelengths of less than about 100μm do not affect the flow.

ACKNOWLEDGEMENTS

We are grateful to the British Ship Research Association (BSRA) and to Ferranti Ltd. for the loan of equipment; to BSRA, Shell International Ltd., Shell Research Ltd., the International Paint Co. Ltd. and Professor Alastair Cameron for roughness specimens and materials. The earlier part of this research programme was supported financially by the Science Research Council. It is currently funded by the Office of Naval Research of the U.S. Department of the Navy

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